Comparison of Hyper-X Mach 10 Scramjet Preflight Predictions and Flight Data

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Outline

- Vision vehicle
- Engine design process
  - Analytical
  - Experimental
  - Data analysis ➡ combustor performance model
- Flight vehicle propulsion database
- Hyper-X flight 3 scramjet propulsion test
  - Surface pressure
- Conclusions
- Acknowledgments

Vision Vehicle

- Dual-Fuel Global Reach vehicle.
- Cruise at Mach 10.
- Hypersonic cruise lifting-body configuration.
- X-43 = 6% scale.
- Demonstrating cruise capability with a subscale vehicle very challenging.
- Re-engine the X-43 Mach 7 vehicle.

Initial Engine Design Process

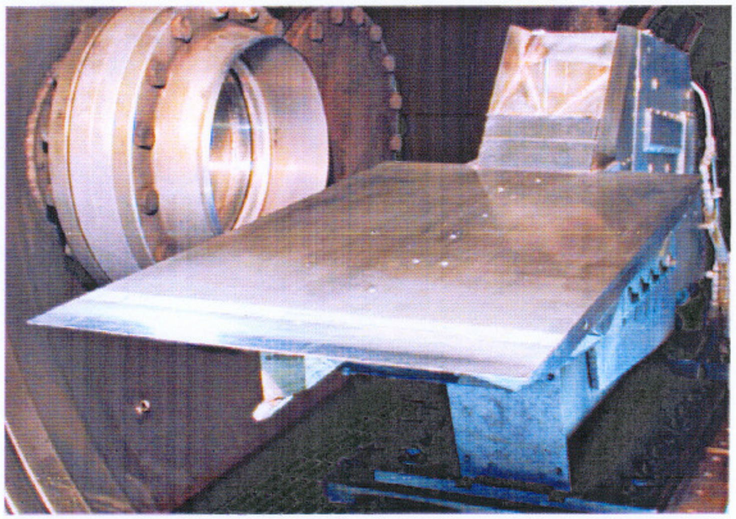
- Engine redesigned not scaled down.
- Vehicle already defined ➡ many constraints.
- Aero database existed ➡ design for vehicle performance.
- Two stage analytical approach.
- First stage: SRGULL tip-to-tail cycle analysis.
  - 3D spillage, η_{KE}, η_c, base pressure
  - M_∞, α, q_{bar}, + 5 geometry variables
- Second stage: GASP & SHIP CFD.
  - Focused on fuel injector design
  - Thermal analysis performed for injector survivability

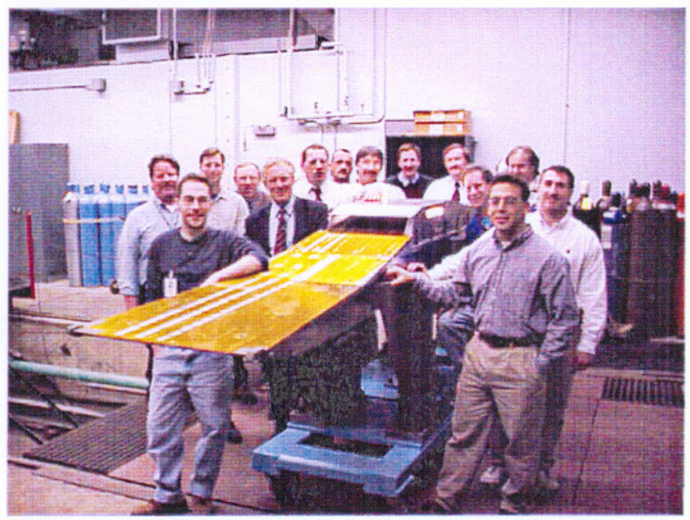
Wind Tunnel Engine Testing

- Unable to test ignition sequence ➡ separate tests with a silane-hydrogen mixture & pure H_2.
- HyPulse reflected shock tunnel
  - Partial width and truncated forebody and aftbody sections
  - Semi-direct connect test configuration
- LENS reflected shock tunnel
  - Full flowpath model with 2D forebody and aftbody sections
  - Free-jet test configuration
- All testing showed a sensitivity to fuel composition ➡ design modified to improve hydrogen only combustion.

Final Engine Testing

- HyPulse: 55 runs at 8 test conditions
  - Mach 9 total enthalpy
  - Mach 10 total enthalpy in 6 configurations
  - Mach 10.3 total enthalpy
- LENS: 20 runs at 4 test conditions
  - Low, nominal, and high dynamic pressure
  - 2° AoA at nominal dynamic pressure



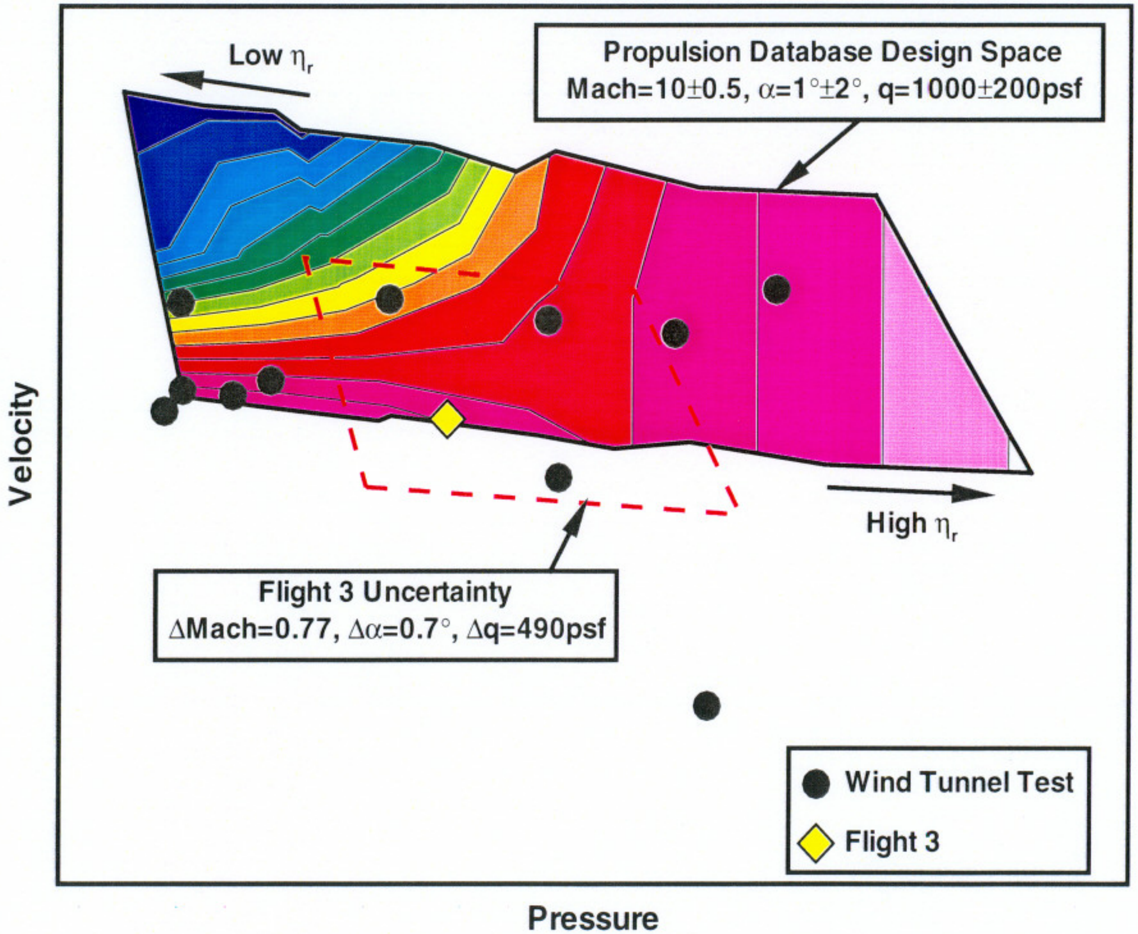


Engine Test Data Analysis

- Consistent methodology applied to every test.
- Goal ➡ determine combustion efficiency.
- GASP – forebody and inlet.
  - 2D, blunt leading edges, transition guided by heat flux data
- SHIP – injectors, combustor, and nozzle.
  - 3D PNS, center slice, 1-step reaction model
  - $\eta_c = \eta_m \bullet \eta_r$
  - η_r schedule determined by matching discrete pressure distribution in the combustor
  - Final η_r based on internal nozzle axial force
  - Relatively easy to perform analysis for silane-hydrogen mixtures

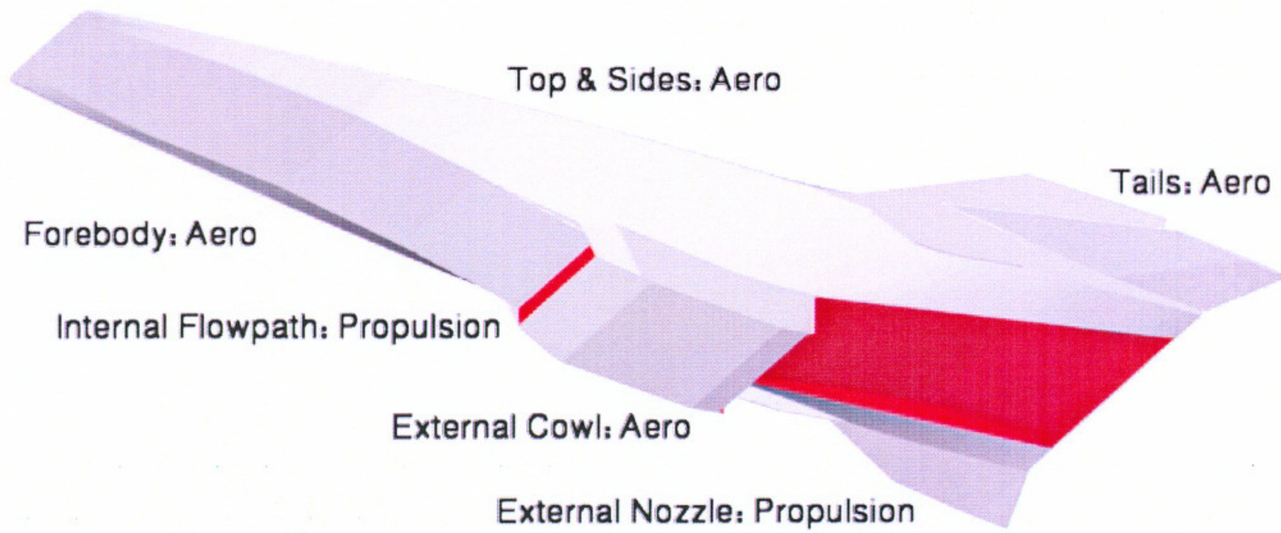
Combustor Performance Model

- Model created from analysis of engine test data



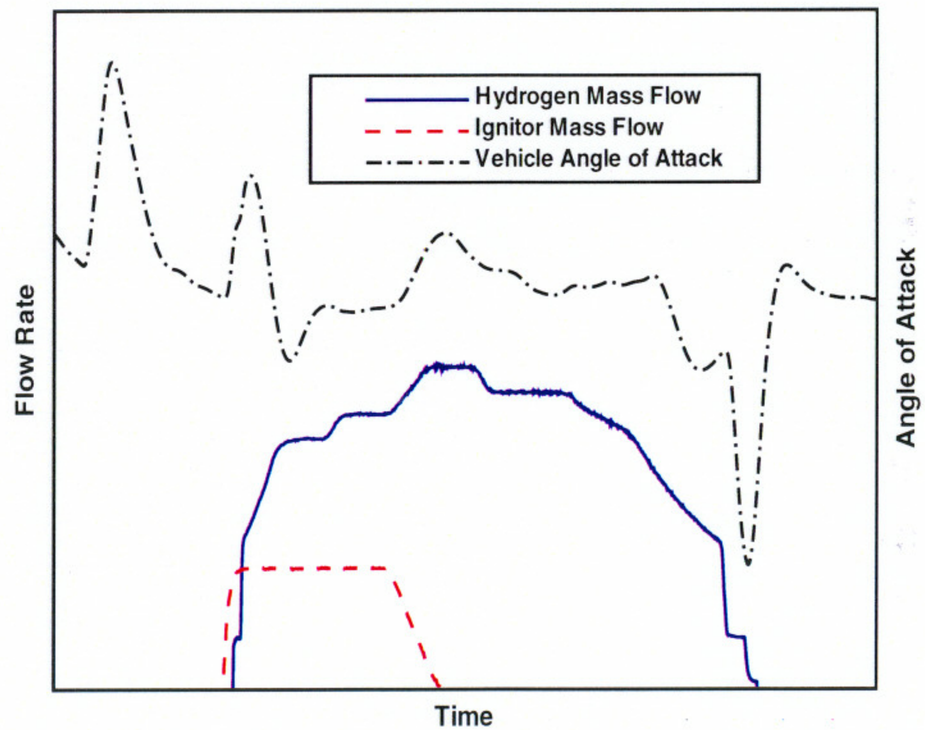
Flight Vehicle Propulsion Database

- Provide engine mass capture, propulsion surface forces and moment over a design space of Mach 9.5 to 10.5, angle of attack -1° to 3°, and dynamic pressure 800 to 1200 psf for both unfueled and fueled conditions.
- CFD database $f(M_\infty, \alpha, q_{bar}, \phi, \eta_r)$.

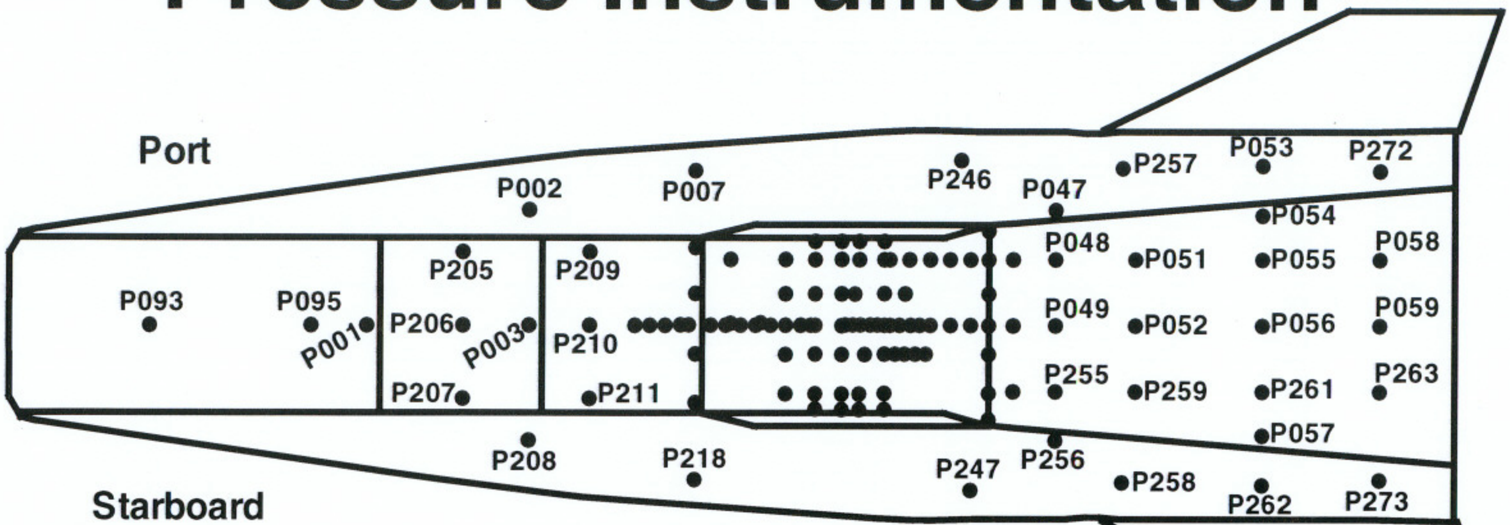


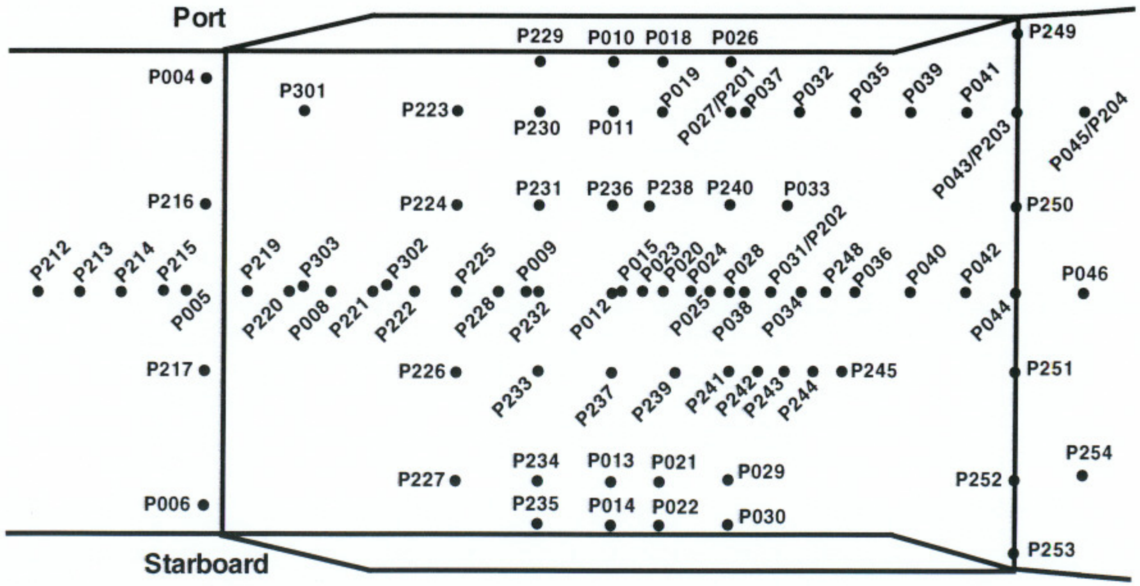
Overview of Flight Test

- Engine fueling sequence designed to match engine wind tunnel test composition and levels.
- Ignitor and H_2 to high levels quickly.
- Gradual transition to pure H_2 .
- Well controlled.
- Duration = 50 times longer than sum total of all final engine tests.



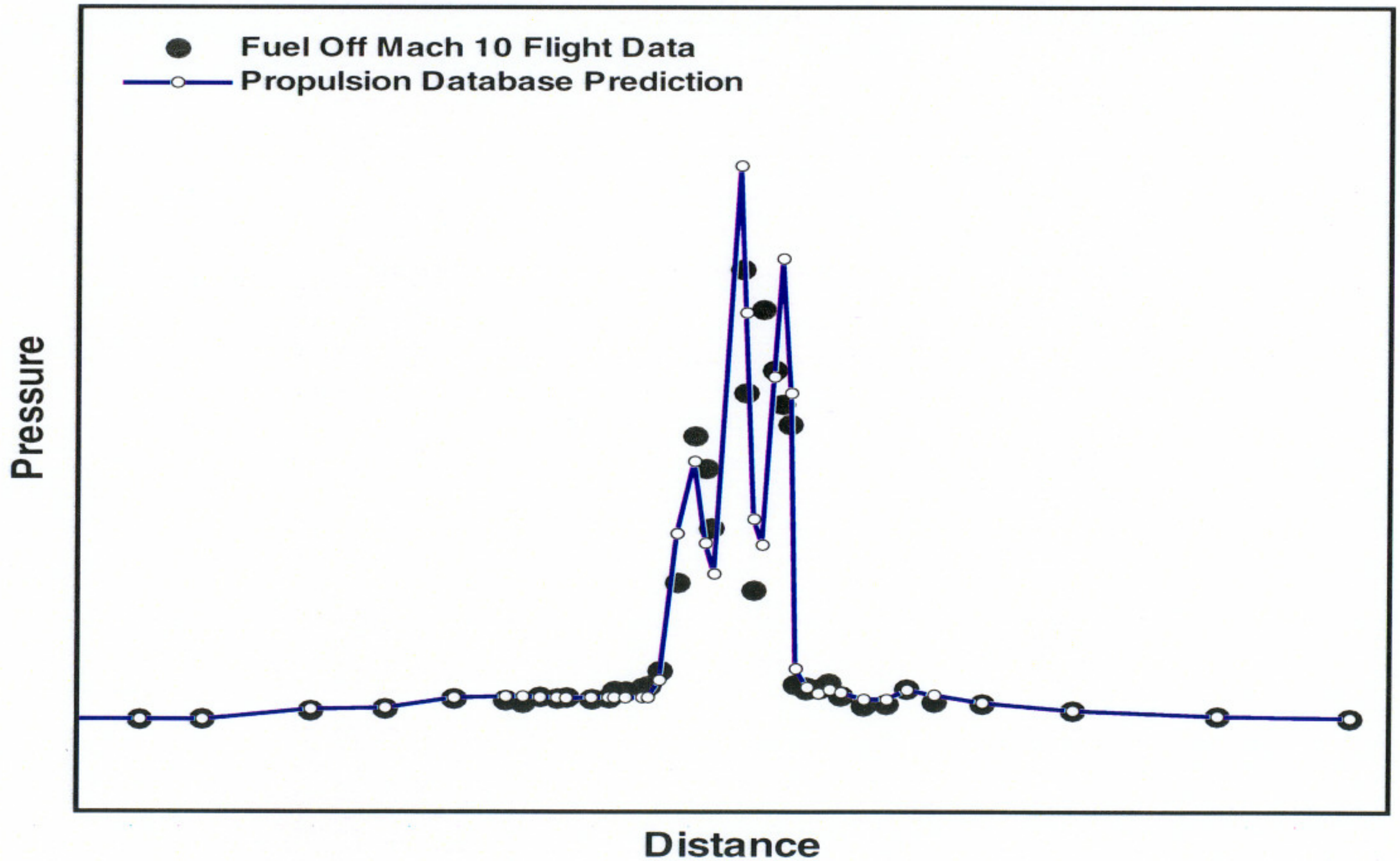
Pressure Instrumentation





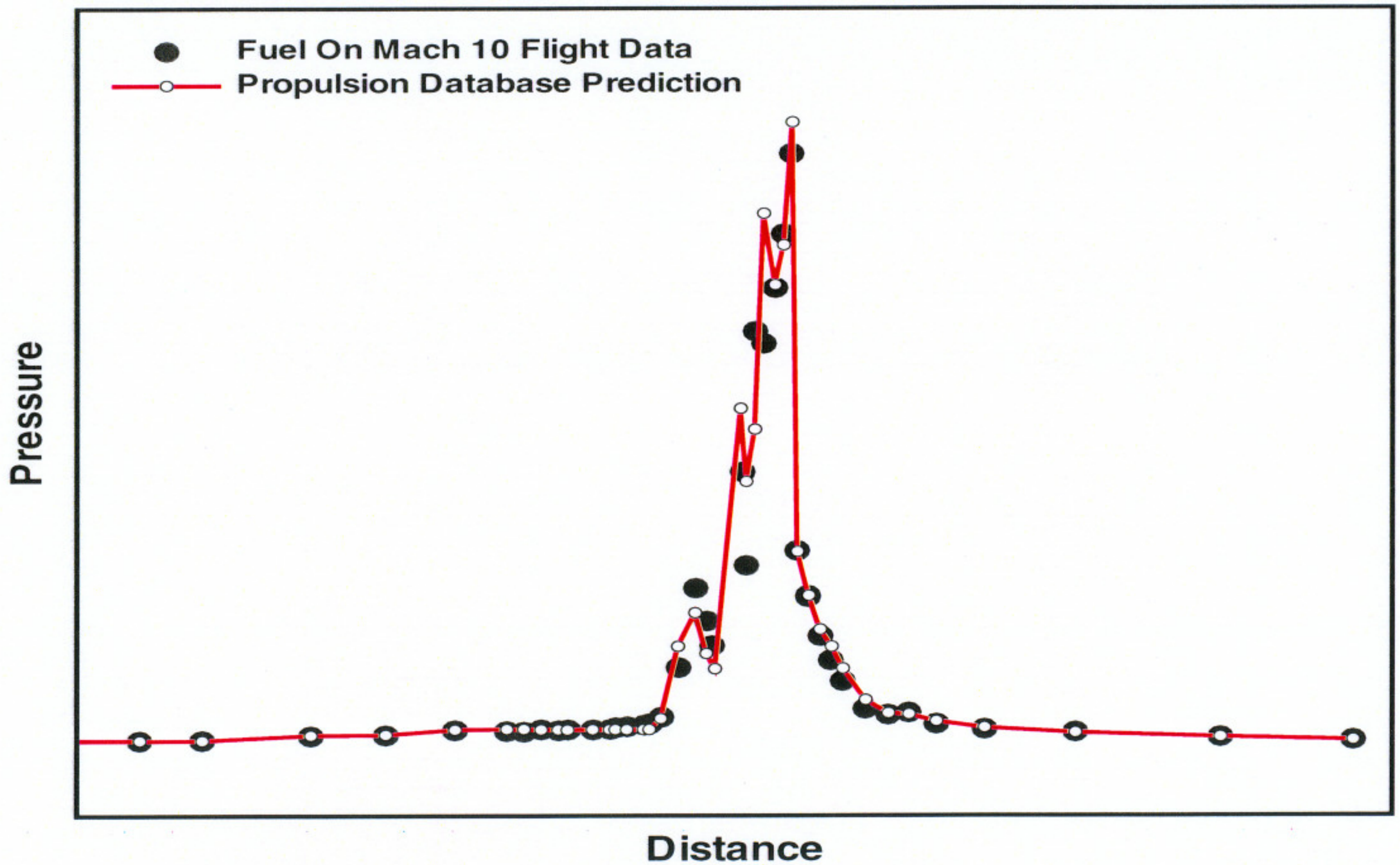
Centerline Pressure Fuel Off

- Shock-dominated flow.
- No nozzle pressurization.

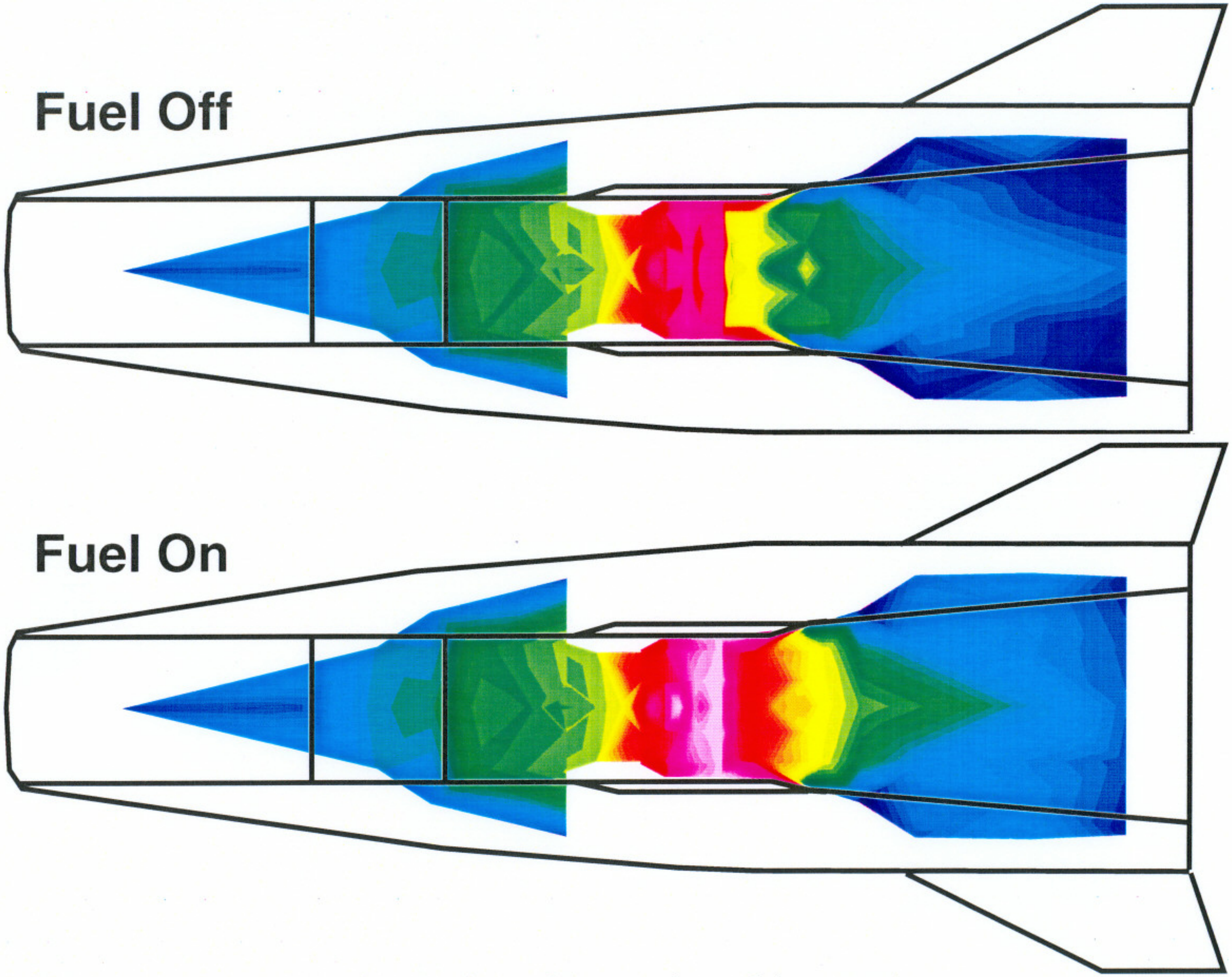


Centerline Pressure Fuel On

- Significant pressure rise.



Surface Pressure Contours



Conclusions

- The Hyper-X program's third X-43 vehicle demonstrated successful air-frame integrated scramjet operation and vehicle control at hypervelocity conditions.
- Good agreement with expectations is an important validation of propulsion testing in pulse facilities and in the computational techniques used to understand scramjet engine test data.
- Demonstrated cruise capability (subscale) at the design cruise Mach number of a vision vehicle, shows that a vehicle could be designed to accelerate through Mach 10 using an airbreathing engine.

Acknowledgments

- Randy Voland and Larry Huebner
  — Hyper-X propulsion team leads
- Shelly Ferlemann — SRGULL calculations
- Robert Bittner — finite rate kinetics and aerodynamic database analysis
- Vince Cuda — fuel injector thermal analysis
- Glenn Bobskill, Tom Jentink, and Ben Meyer
  — GASP calculations
- Clay Roger, Ann Shih, and David Witte
  — engine ground test program